NF Note 28
16th August 2000

The CERN Neutrino Factory Working Group Status Report and Work Plan

B. Autin, J.-P. Delahaye, R. Garoby, H. Haseroth, K. Hübner,
C.D. Johnson, E. Keil, A. Lombardi, H. Ravn, H. Schönauer [1]
A. Blondel[2]

1 Introduction

The production of neutrinos from the decay of muons circulating in a storage ring (neutrino factory) has of late attracted considerable attention. The original interest started with the study of muon colliders [1,2]. These colliders could open the way to lepton collisions at extremely high energies. Circular electron colliders are limited in energy due to the high synchrotron radiation emitted by the electrons. Although this radiation decreases with larger radius of the accelerator, it increases with the fourth power of the energy. For this reason it seems unrealistic to build circular machines with higher energies than LEP. The only possibility for higher energies seemed to be linear colliders with all their technical challenges. Another solution is the use of heavier leptons in circular colliders, as the limiting synchrotron radiation power at the same energy is inversely proportional to the fourth power of their rest mass, γ^4. Muon beams seem to be possible candidates for this purpose. Muons can be produced by the decay of pions, which in turn can easily be produced by bombarding a target with high-energy protons. The most serious problem is the production of muon beams with the high phase-space density necessary for collider operation. In spite of some impressive progress towards this goal, no technically feasible solution has yet been found. A substantial R&D effort will be required to make progress.

With the recent confirmation of neutrino oscillations, the situation has changed drastically. High-energy muons, stored in a decay ring with long straight sections pointing towards distant detectors, provide a unique beam of high-energy electron neutrinos. This allows precise determination of several parameters of the neutrino mass matrix, possibly including the CP violating phase, which would otherwise be inaccessible. The reduced requirements (compared to a muon collider) of this neutrino factory have brought much closer to reality the concept of high intensity muon machines. The R&D effort for the muon colliders turns out to be very useful for a neutrino factory, and the increased interest from the physics side has produced a spate of activity on the accelerator side, so that considerable progress has been made towards a neutrino factory design [3,4,5]. It is interesting to note that, in turn, a part of this progress is also beneficial for the design of a muon collider.

---

[1] This CERN group has edited the report. It is based on the work of the whole Neutrino Factory Working Group.
[2] University of Geneva, Convenor of MUG

CERN is proposing a reference scenario, which serves as guide line for its activities in this direction. With the help of other laboratories, CERN has initiated a study on some of the many technological challenges of such a facility. Discussions about the exact scope of the different collaborations are under way.

2 The basic concept of the CERN neutrino factory scenario

The reference scenario described here is based on a particular situation at CERN. It is intended as a working hypothesis that is in part CERN specific, while being dominated by the wish to achieve the required high muon fluence [26].

The requirements, as expressed in the Nufact99 workshop at Lyon [11], set a target fluence of 10^{21} muons per year injected into the storage ring. The present CERN accelerators are not suited to easy upgrade of the available beam power. However, a proposal [6,7] has been made to replace the CERN PS injector complex (50 MeV linac and 1.4 GeV booster) by a linear accelerator, destined primarily as injector into the PS for the LHC beam. It is intended to offer a higher brilliance LHC beam from the PS. The basic idea in proposing to build this linac is to re-use the cavities, klystrons and auxiliary equipment from LEP after this machine has been shut down. Average beam power.of 4 MW appears to be feasible. We envisage in our scenario a beam energy of only 2.2 GeV, which is low, compared to other proposals. The results of the HARP experiment [9], which will measure pion production in this energy range, should produce data next year and this will be crucial in the final assessment of our choice.

A neutrino factory requires the production of beam pulses consisting of relatively short trains of very short proton bunches (nanoseconds). This allows the use of bunch rotation to reduce the large energy spread within the muon bunches. The pulse repetition rate must not be too high; otherwise the energy consumption of the subsequent machines becomes too high. Also it would be wasteful if a new injection into the storage ring took place before the previous batch had decayed (the ring design employs full-aperture kickers and so injection kills the previous circulating muon beam). The linac cannot directly provide a suitable beam; hence it will operate with H^- ions and inject into an accumulator ring, using charge exchange injection to achieve a large circulating proton current. Bunches will be formed in this ring with suitable rf cavities. They will be transferred into a compressor ring for further shortening of their length. The linac will operate at 75 Hz and initial pulse duration of 2.2 ms at a mean current of 11 mA during the pulse. After accumulation and compression the resulting beam pulses, now shortened to 3.3 μs - the revolution period in the accumulator and compressor rings, contain a bunch train comprising 140 bunches spaced at 44 MHz frequency. The repetition rate is 75 Hz. It is assumed that the accumulator and compressor rings will be accommodated in the old ISR tunnel.

This beam will irradiate the production target. In the FNAL study [5] a stationary carbon target has been chosen. This has many advantages, but it is only applicable to the lower beam power assumed in this study and for the higher energy of their proton driver. In our case at 4 MW and 2.2 GeV, to ensure adequate cooling we must use a moving target. Some work has begun at RAL on the development of a moving toroidal target made out of solid material; an alternative possibility is a liquid (metal) target. Some liquid metal experience is available at CERN and we plan to investigate this option.

It is necessary to capture the pions produced in the target. The FNAL study has chosen for this purpose a 20 T solenoidal field. The solenoid magnet is expensive and needs substantial maintenance, especially when used around a target exposed to high beam power. At CERN there is considerable experience with magnetic horns, for the collection of antiprotons and in the production of (conventional) neutrino beams. It is therefore worthwhile to investigate the possibility of using a magnetic horn also for the neutrino factory.

Because of the high repetition rate and the large number of bunches, an rf system is proposed for the manipulation of the muons after the pion decay. The rf system will capture and phase-rotate the muon bunches, and it will also be used in the ionisation cooling of the muon beam. Further acceleration of the muons to 2 GeV is performed in a special linac with solenoid focusing up to around 1 GeV, followed by more conventional quadrupole focusing. Subsequent acceleration takes place in two Recirculating Linacs (RLA) to an energy of 50 GeV. The muons are then injected into a storage ring (decay ring) where they are kept for the duration of the useful beam lifetime (1.2 ms at this energy). The muons decaying in the long straight sections of this ring produce the required neutrino beams. A schematic layout of this CERN reference scenario is presented in Figure 1.

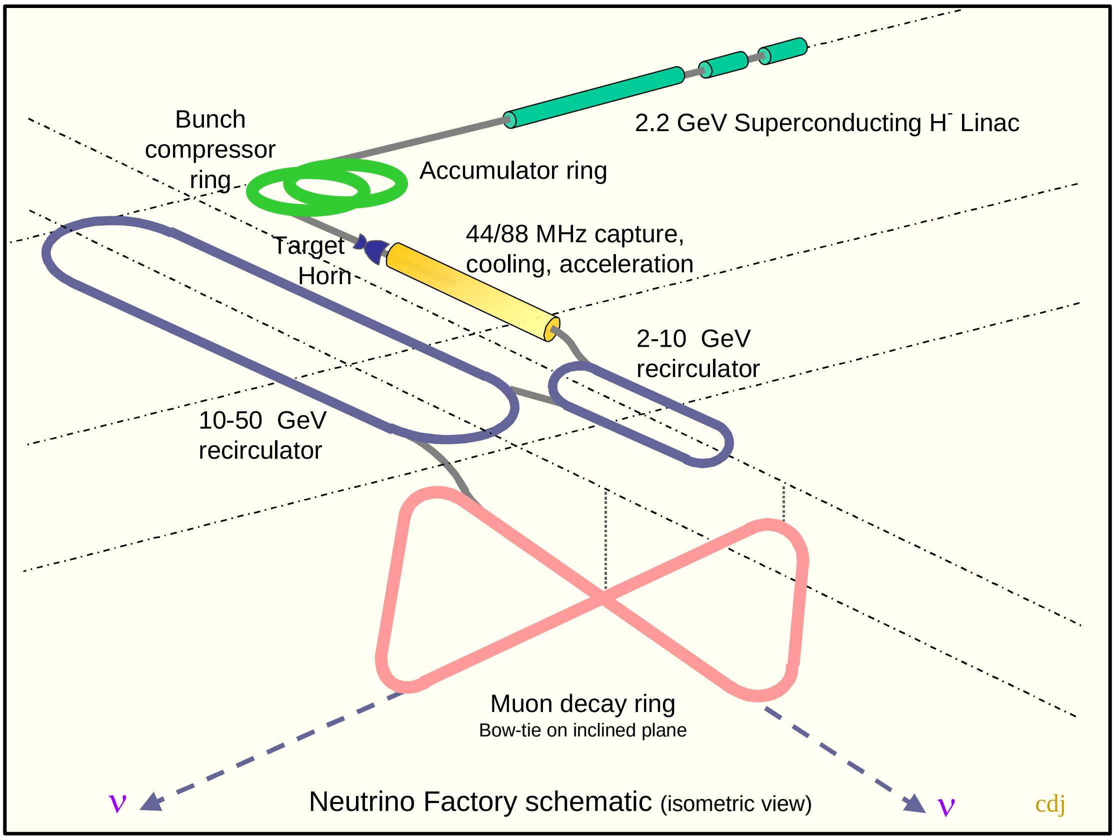

Figure 1 Isometric schematic of the CERN reference scenario for a Neutrino Factory

3 Brief description of individual subsystems of the reference scenario

3.1 The SPL Study

3.1.1 Present design

The Superconducting Proton Linac (SPL) accelerates H^- up to 2.2 GeV kinetic energy in bursts of 2.2 ms duration, at a rate of 75 Hz. The mean current during the pulses is 11mA for an average beam power of 4 MW. The main characteristics of the SPL beam are listed in Table 1. For the neutrino factory the beam burst is accumulated over 660 revolutions of the accumulator ring that transforms it into a 3.3 μs train of 140 bunches. These are then individually reduced in length in a compressor ring before being sent to the pion production target. Table 1 summarises some of the parameters of the SPL in this mode of operation.

Beam Current, mA	11
Energy (kinetic), GeV	2.2
Invariant transverse rms emittance, μm	0.6
Beam energy spread (√5σ) MeV	±2
Bunch length (total: √5σ), ps	24
Linac length, m	800
rf frequency, MHz	352
Overall rf power, MW	31
Number of klystrons	46

Table 1 The 2.2 GeV Superconducting H^- linac parameters in quasi-CW mode

The beam from the ion source is bunched at 352 MHz by an RFQ and chopped at 2 MeV to minimise capture losses in the synchrotron accumulator. Conventional room temperature accelerating structures are used up to 120 MeV. Above this energy superconducting rf cavities are employed. Up to 1 GeV, new low-beta structures are needed, while 116 LEP-2 cavities in 29 cryostats are used afterwards (Figure 2).

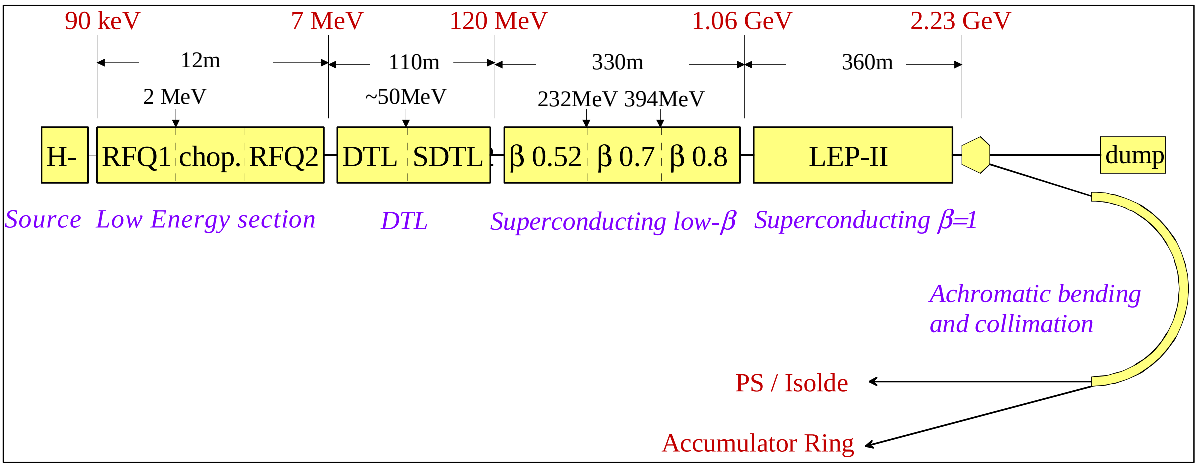

Figure 2 Layout of the Superconducting Linac

The entire rf infrastructure and all cavities between 1 and 2.2 GeV can be built from recuperated LEP hardware, leading to a cost-effective machine. The main new elements to be constructed are:

1. The 120 MeV room temperature Linac
2. The new low-beta superconducting cavities for the section between 120 and 1000 MeV
3. The focusing ,diagnostic and control equipment
4. The cryoplant
5. The civil engineering for the 800 m accelerator tunnel and the technical gallery

Radiation handling is a key concern at these high beam powers. In order to permit hands-on maintenance, losses must be kept below 1 W/m, a challenging figure that requires an adequate machine design with a careful control of beam halo as well as an effective collimation systems. The large aperture of the LEP-2 cavities is an important advantage in this respect because most of the halo particles that develop after the initial collimation are transported to the end of the linac and dumped in collimators where radiation issues are localised and properly addressed.

3.1.2 Potential evolution

The design of the muon collection, cooling and acceleration is still evolving. The choice of the actual SPL characteristics is based upon the recently proposed CERN scheme [8], which defines the parameters for the 2.2 GeV proton beam hitting the target. Any evolution of the scheme will have consequences on the proton driver. The CERN HARP experiment [9] will determine the efficiency of protons of various energies for the production of pions and muons. Depending on its results, the interest of 2.2 GeV protons will either be confirmed or not. This will have important consequences for the future of the SPL proposal.

3.2 Other uses of the SPL

Although re-designed for the needs of a neutrino factory, the attractiveness of the SPL is that can replace the present injectors of the PS and improve its performance. The brilliance of the proton beam for LHC in the PS can be doubled and the maximum PS intensity can be increased by a substantial amount with immediate benefits for users like SPS in fixed-target mode (CNGS). Moreover, the present ISOLDE facility can be supplied with a beam which is up to 5 times more intense (up to 10 μA, limited by the present ISOLDE lay-out) and better matched to the target capabilities, without interfering with the PS needs. In a future stage, the next generation ISOL facility, as discussed in the new NuPECC report [31], which will need up to 100 μA, can also be accommodated.

The proton beam from the SPL may also be used for high-intensity stopped-muon physics and to produce a low-energy neutrino beam in the conventional way. A study of the interest for such a beam is being conducted in the Physics Working Group.

3.3 Accumulator and Compressor Ring

The CERN reference scenario uses the 2.2 GeV SPL (Section 3.1) combined with an accumulator and a compressor ring that could be situated in the ISR tunnel [27]. The ring parameters (Table 2) have followed the evolution of the SPL study, and are now well adapted to the parameters of the 44 MHz rf muon phase rotation, cooling and acceleration section. The choice of this rf frequency determines the harmonic number of h = 146. Consequently140 bunches (plus 6 empty buckets) fill the circumference of both rings. The repetition rate has been chosen to be 75 Hz.

	Accumulator	Compressor
Circumference, m	945	945
Beam kinetic energy, GeV	2.2	2.2
Revolution period (β=0.954), µs	3.3	3.3
rf harmonic number	146	146
Number of turns	660	~7
Repetition rate, Hz	75	75

Table 2 Main parameters of accumulator and compressor rings

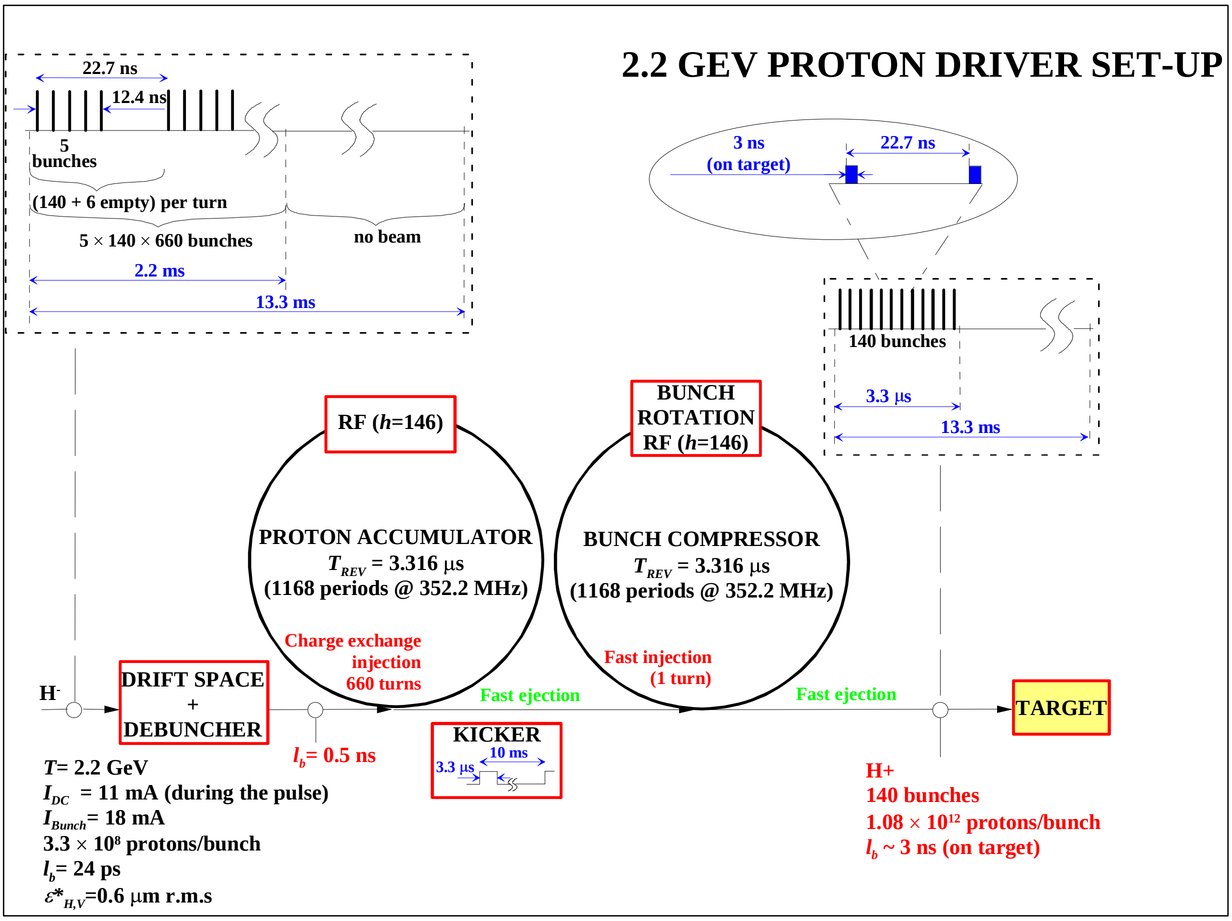

Figure 3 Accumulator Compressor scheme for a Neutrino Factory

Contrary to initial ideas of designing nearly isochronous lattices to economise rf voltage, both rings now feature high-γ_t lattices ensuring fast debunching of the very short (0.5 ns) linac microbunches as well as very fast rotation (~7 turns) in the compressor. The high γ_t raises the synchrotron frequency and is thus also instrumental in smoothing the accumulated distribution in longitudinal phase-space. The feasibility of H^- injection (injecting 660 turns could entail intolerable foil heating) and of the final bunch rotation has been shown. Simulations including the effect of space charge on momentum compaction and of the microwave instability have not revealed any problems. Both accumulator and compressor lattices are designed; details of the intersection and the transfer between the rings remain to be studied. A schematic of the accumulator/compressor scheme detailing the bunch time structure is shown in Figure 3.

3.4 Target and Pion Capture

The contacts to the community of people and laboratories outside CERN who expressed an interest to participate in high power target and beam-dump development at the NuFact99 workshop is maintained and is being extended to new laboratories. The details of two target concepts in which either solid or liquid target-material is re-circulated in the beam are being addressed by simulations and discussions.

A number of ideas are under consideration which in principle should allow a beam power on target power of up to 4 MW. The crucial problems are mechanical movements in high magnet fields, heat transfer, material stress, radiation damage and radioactivity confinement. Laboratory tests of the simulations and determination of engineering parameters should be the next step in order to select the future directions among the many ideas around.

Equipment and expertise on liquid mercury technology exists at CERN and we believe that this is the most promising direction. Some preliminary tests of the hardware requirements for a liquid jet target, initiated as a part of the Muon Collaboration, have recently been completed [10]

Since one is interested in the production of one sign of pions for any given proton bunch, one could envisage a pion collection system based on azimuthal magnetic fields generated by a horn. A major advantage of horns is that the parts exposed to the beam are rather simple, inexpensive and can be radiation hard. The horn should be designed to focus particles emitted at large angle, and with a momentum range of 200-400 MeV/c, from a target of typically typically 2-interaction lengths. The horn design will be rather different from those used for high-energy beams, such as CNGS and NuMI, and closer to those considered for the antiproton source or the Fermilab mini-Boone beam

3.5. Muon Capture, Phase Rotation, Cooling and Acceleration

During the period September 1999 - May 2000 beam dynamics studies for the front end of a neutrino factory have been going on in the PS division. The front-end of the neutrino factory is a system that is designed to collect the pions produced in the target, to phase rotate and cool the muons and finally to accelerate the muons to 2 GeV for injection into a re-circulator.
After a first period of familiarisation with the problematic and the computer codes the beam dynamics for the following possible solutions has been explored:

1. A solution employing an induction linac for reducing the energy spread of the muon beam and a cooling section employing 176 MHz rf cavities and liquid Hydrogen. This solution is of the type adopted in the Fermilab feasibility study [5].
2. A solution employing 44 and 88 MHz rf cavities for the phase rotation and the cooling. The cooling is achieved by a series of rf cavities interspersed with low-Z material that reduces the momentum of the muons by ionisation. This is assumed to be liquid hydrogen. The rf cavities restore the longitudinal but not the transverse momentum. The net effect is a reduction of the transverse emittance.

The first two solutions were studied to the same level of accuracy (end-to-end beam dynamics simulation) and their muon yield turned out to be comparable. Details can be found in NF notes 16,17 and 20 [12,13,8]. The induction linac solution has been thoroughly studied at Fermilab and LBNL, including engineering constraints. The 44-88 MHz solution has been studied for a shorter time and was presented outside CERN for the first time at Nufact00 [31]. The feedback was positive with very useful comments and generally encouragement. The scheme was compared to the other proposals [4,5]. The performances in terms of muon/proton GeV are comparable. The 44-88 MHz scheme is more suited to the CERN preference for a driver at 2.2 GeV and it draws on our expertise in 40 MHz rf cavity technology [30].

The 44-88 MHz system

After the target the pions are allowed to decay in a 30 m long channel focussed by a 1.8 Tesla solenoid. At the end of the decay channel the particles with kinetic energy in the range 100-300 MeV are captured in a series of 44 MHz cavities and their energy spread reduced by a factor two. At this point a first cooling stage, employing the same rf cavities, reduces the transverse emittance in each plane to 60%, while keeping the final energy constant. After the first cooling stage the beam is accelerated to an average energy of 300 MeV. The longitudinal bunching achieved with acceleration as well as the reduced physical dimensions of the beam allow us to employ an 88 MHz cavity cooling system. The second 88 MHz cooling stage, mixed with acceleration and rebunching, is continued till a sufficient number of particles fit within a 6D invariant emittance volume defined by 15 pi mm in the two transverse planes and 0.053 eVs in the longitudinal plane. The first recirculator (RLA1) defines this admittance. The beam is then accelerated to 1 GeV with 88 MHz cavities. Present calculations estimate some 10^{21} muons/year (assumed to be 10^{7} seconds of operation) delivered to the re-circulator. The main characteristics of the components are reported in Table 3.

	Decay	**Rotation**	**Cooling-I**	**Acceleration**	**Cooling-II**	**Acceleration**
Length, m	30	30	46	32	112	≈450
Diameter, mm	600	600	600	600	300	200
Solenoid field, T	1.8	1.8	2.0	2.0	2.6	2.6
Frequency, MHz		44	44	44	88	88-176
Gradient, MV/m		2	2	2	4	4-10
Energy, MeV		200		280	300	2000

Table 3 Main parameters of the capture, phase rotation, cooling and acceleration section

RF system

The underlying motivation for this set-up is to make use of hardware with little extrapolation from existing technology. Based on experience with 44 MHz CERN-PS cavities [14] and analysing with SUPERFISH the characteristics of resonator geometries that could fit the needs of the muons sections, encouraging results have been obtained. Keeping a bore radius of 30 cm, and 25 cm around the bore to house a solenoid, a solenoid, a useful gradient of 2 MV/m at 44 MHz is obtained with

0.8 MW peak rf power [15]. With a similar design at 88 MHz of bore radius 15 cm, a real estate gradient of 4 MV/m is achieved at an rf power of 1.8 MW. The mean rf power consumption to operate all the 200 m of the Rotation and Cooling sections at 75 Hz is estimated to be12 MW.

Future simulation work

As a consequence of the positive outcome at NuFact00 it has been decided that the 44-88 MHz system is to be included in the present CERN reference scheme and all the available manpower for beam dynamics should concentrate the effort on a more-depth study of this system. The present simulations use ideal rf and solenoidal fields and do not yet include the material for the windows of the rf cavities, nor the necessary material for the containers of the liquid hydrogen required for the cooling. These issues need refinement of the data for the simulation programs and will be addressed in the near future.

In addition, the future beam dynamics simulation work will include:

1. An assessment of the dependence of the muon yield from the proton beam characteristics and the target material and geometry (limit on the upstream parameters).
2. Optimisation of each section (minimise emittance growth during decay, optimise cooling, a more refined design of the final accelerator).
3. In parallel, a revising of the beam dynamics in view of engineering constrains.

The current transmission efficiency of the system, taking into account the admittance of the RLA1, can be seen in Figure 4. Finally a sensitivity study to the rf and mechanical parameter should be done to measure and optimise the stability of the system.

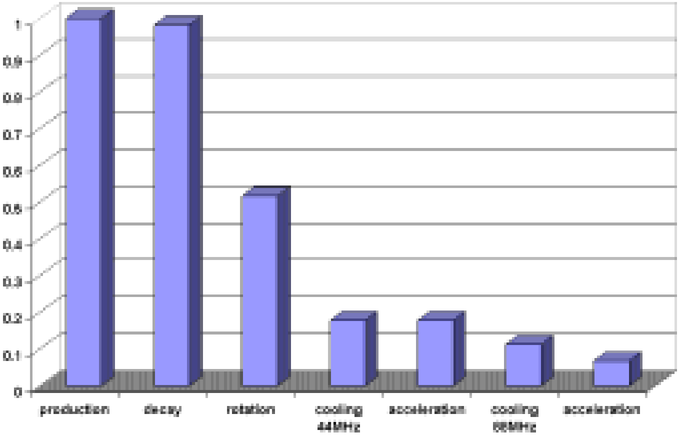

Figure 4 Transmission along the 44-88 MHz system

The fundamental components of the 44/88 MHz system for phase rotation are the 44 MHz cavities. Some of the open questions are:

1. What is the minimum thickness of the window?
2. What is the maximum gradient that can be achieved in the cavity (anything from 1 MV/m up is accepted but a higher gradient would reduce the length of the system)
3. Can a superconducting solenoid be fitted around the cavity?

4. Can a superconducting solenoid stand the losses due to muon decay and/or should it be screened and/or collimation system envisaged?

With the manpower presently available it is estimated that a more detailed study including engineering constraints can be achieved by early next year. This time scale relies on the strengthening of the team as foreseen for the near future. The optimisation of the system will continue at least till mid 2001

After the beam is cooled, the acceleration is continued using 88 MHz cavity of the same type and solenoid focusing until the beam has reached 1 GeV when a transition to 176 MHz rf and quadrupole focusing is possible. The accelerator design has not yet been optimised. In the present scheme there is no assumption of transverse emittance growth, little (a few percent) longitudinal loss and 20% losses due to muon decay. An optimisation should allow us to shorten the linac and, perhaps, shift to the higher frequency at a lower energy.

3.6. Recirculating linear accelerators

Two recirculating linear accelerators muRLA1 and muRLA2 accelerate the muon beams from 2 to 10, and from 10 to 50 GeV, respectively. Their design concept [16] has some similarities with that of ELFE at CERN [17]. Their shape is that of a racetrack. Their circumference is about 1 and 5 km, respectively. The straight sections are occupied by super-conducting linear accelerators with a peak voltage of 1 and 5 GV, respectively, consisting of LEP cavities with 7 MV/m gradient. The muon beam passes through each of them four times. The muons are accelerated on the crest of the rf wave. The transverse focusing in the linear accelerators is arranged to have constant betatron wavelength on the first pass. Spreaders at the output end of the linear accelerators feed the muon beams into four separate, vertically stacked arcs. Combiners merge the four beams into the input end of the next linear accelerator. The lattice of the arcs consists of achromats, modified such that all passes through spreader, arc, combiner and linear accelerator are isochronous. Detailed parameters are listed elsewhere in this document.

The optical design of the linear accelerators and of the arcs is pretty straightforward and poses no particular problems. This is not true for the spreaders and combiners; in particular in the first recirculating linear accelerator muRLA1 that must handle a muon beam with an initial energy spread of approximately 12.5%. This large energy spread is one of the reasons why the number of passes is only four.

The concept of recirculating linear accelerators, operating isochronously at the crest of the rf wave, implies that there are no synchrotron oscillations, and that the bunch length and the absolute energy spread in the muon beam are fixed. Hence, the relative energy spread is adiabatically damped like 1/E. The concept also imposes an upper limit on the bunch length that is caused by the shape of the rf wave and indeed tighter than that from the size of the rf buckets in the muon storage ring. The muon collection and cooling systems and the linear accelerator for the muons up to 2 GeV can meet these requirements. It remains to be demonstrated that this concept works. The concept adopted in the FNAL study [5] is an alternative. There, the muons are accelerated off the crest of the rf wave, the arcs are anisochronous, and the synchrotron tune does not vanish. A list of the main parameters is given in Table 4.

	RLA1	**RLA2**
Injection energy, GeV	2	10
Extraction energy, GeV	10	50
Number of turns	4	4
Length of linacs (2), m	680	3813
Rf frequency, MHz	352	352
Bending radius in arc, m	5	25
Mean arc radius, m	20	100
Circumference, m	806	4442
Peak voltage gradient per linac, MV/m	7.4	7.4
Normalised admittance, mm rad	16.47	18.80
Normalised rms emittances, mm rad	1.83	2.09

Table 4 Main parameters of recirculating linacs

As is the case with the muon storage ring, the design of the recirculating linear accelerators is based on a series of assumptions concerning their engineering and the parameters of the muon beam. Once the feasibility of one or the other concept for muRLA1 and muRLA2 is established, all these assumptions ought to be questioned. If the assumed accelerating gradient was higher than 7 MV/m, the circumference of muRLA1 and muRLA2 would reduced almost in proportion, and so would be the decay losses. In the present design, about 77% of the muons survive through muRLA1 and muRLA2. However, the length of muRLA1 is chosen according to another criterion: such that the muon beam fills the recirculator, i.e. so that the muon revolution period in the RLA1 is the same as the proton revolution period in the compressor ring[3]. This facilitates the beam loading compensation based on the beating of two sets of rf cavities with slightly different frequencies.

3.7. Muon storage ring

A design [18] was completed for a muon storage ring that fully meets the requirements of the Neutrino Oscillation Working Group, i.e. 50 GeV muon energy, 10^{14} muons/s arriving in the storage ring for 10^7 s/year. A list of the main parameters is given in Table 5. The machine has the shape of an equilateral triangle with rounded corners. It has two long straight sections feeding neutrinos to detectors at 1000 and 3000 km distance with a muon beam divergence of less than 0.2 mr. A third long straight section closes the machine and is used for tuning. The machine is installed in a plane that is inclined such that the pitch angles in the long straight sections are: -78.9, -237.9 and +319.6 mr. The triangular shape fixes the relative directions pointing towards the two detectors. Small deviations from the assumed shape are easy. Large deviations are undesirable because they imply steeper slopes.

Several tens of thousand muons were tracked for the full muon lifetime. Collimators at 3-rms beam radius in almost all quadrupoles limit the physical aperture. Muons with initial offsets 2.4 rms beam radii in both horizontal and vertical directions survive. A dynamic aperture problem caused by the fringe fields of six quadrupoles was overcome by doubling their length [19]. The long straight sections should contain the smallest possible number of active components. One possibility is to use permanent-magnet quadrupoles [23]. The average energy deposition around the circumference of the

---

[3] This condition is not yet met exactly.

muon storage ring, due to decay electrons, is about 140 W/m. Its enhancement, caused by electrons originating in the long straight sections and getting lost at the beginning of the arcs, has been investigated [29,21]. Two extreme possibilities for the removal of the heat due to decay electrons, about 70 kW in a straight section of 500 m length, are a shielded vacuum chamber with water cooling at room temperature or a transparent vacuum chamber and regularly spaced, water cooled absorbers.

Design momentum, GeV	50
Muon fluence, s^{-1}	10^{14}
Configuration	Triangular
Normalised beam divergence in SS at σ_ε, mrad	0.1
Normalised beam emittance (σ_ε), mm rad	1.67
Aperture limit	3 σ_ε
Relative rms momentum spread	0.005
Bunch spacing, mm	851
Dipole field, T	6
Total length of straight sections, m	1500
Average radius in the arcs, m	46
Circumference, m	2075

Table 5 Main parameters of muon decay ring

A muon storage ring with the shape of a symmetrical bow-tie [22] and long straight sections also feeding neutrinos to detectors at 1000 and 3000 km distance with a muon beam divergence of less than 0.2 mr was also studied. Its parameters are close to those of the triangular machine. The bow-tie shape has some advantages in terms of site layout and flexibility of orientation. It is the form that has been used in the schematic neutrino factory depicted in Figure 1.

According to the CERN survey group, the survey and alignment is possible at the required accuracy of 10^{-5} rad for aiming at the far detectors. This accuracy can be achieved, provided that vertical shafts near the ends of the long straight sections allow transferring GPS coordinate readings from the surface of the Earth into the tunnel. These shafts are needed anyway for a variety of reasons.

The beam optics of the muon storage should only be studied further, once the results of the engineering and beam parameter studies provide enough guidance. At some point, the question should be addressed what diagnostic equipment is needed, and where, in the muon storage ring.

4 Alternative Solutions

4.1 Proton Driver Rings -- Design Strategy and Reference Scenario

In view of the uncertainty of some crucial specifications like pulse repetition rate, a number of 4 MW proton driver scenarios have been studied. From these studies emerged the Reference Scenario described in Section 3. Here we mention the alternative proton driver scenarios that have been studied:

Collaboration with RAL was established for the design of a site-independent synchrotron driver scenario. 5 GeV, 50 Hz and 15 GeV, 25 Hz machines were investigated, the latter using the ISR tunnel. Each one requires two booster and two driver rings. Lattices have been designed and the H^- injection and final bunch compression have been studied and shown to be feasible. The 180 MeV, 56mA H^- linac is very similar to the existing ESS design and has been appropriately adapted. The study of this scheme is being pursued at RAL [28].

In the case that a slow repetition rate will ultimately be needed, we opted for a 30GeV, 8Hz configuration, using the ISR tunnel for the driver [29]. This high beam energy allows injection into the SPS above its transition energy, thereby holding the promise of an intensity increase for the LHC and for fixed-target physics. The high-γ_t lattice of the latter provides naturally short bunches without compression. The feasibility of the approach has been demonstrated by tracking studies including high-Q longitudinal impedances of resonance frequencies up to the pipe cut-off. The lattices designed so far are no standard types and need refinements, and it is likely that the extraction energy has to be reduced to 25 GeV, still useful for the SPS. The 2.2 GeV booster ring delivers 440 kW beam power at 50 Hz and would upgrade ISOLDE.

4.2 Pion capture

As mentioned in Section 2, the alternative scheme for pion capture after the target replaces the magnetic horn by a high-field solenoid. This has been the solution adopted in all previous studies. Since it has been studied in more detail than the solution with a magnetic horn, the simulations of the 44/88 MHz muon capture and cooling scheme are based at present on data from pion production and capture in a 20 T solenoid.

5 Proposed R&D

Herewith is a non-prioritised list of R&D topics that are associated with this CERN reference scenario. A forthcoming task is to order these topics into a programme of work on a CERN, European and World basis.

5.1 SPL

All equipment should be studied to prepare for the design of the SPL. In terms of priority and taking into account the developments in other laboratories, the most important ones are:

1. The β=0.52 and 0.7 superconducting Nb/Cu rf structures (an adequate solution has been found for β=0.8)
2. The room-temperature Drift-Tube Linac between RFQ and SC linac,
3. The H^- source,
4. The design of field regulation servo-loops for the SC cavities
5. The 2 MeV chopper, and especially its driving amplifier.
6. The 60 kW rf amplifiers used in the low-beta sections of the SC linac

The machine layout must be refined using the results of these hardware developments and the outcome of extended beam dynamics studies including the analysis and minimisation of halo and beam loss.

5.2 Target

Most of the work is at present being done in the US and at the following European laboratories outside CERN:

Grenoble University. Pion production calculations.
Grenoble High Magnetic Field Laboratory. Potential partner in target solenoid tests.
GANIL Interested in molten metal target technology
GSI Interested in molten metal target technology
MOL Interested in molten metal target technology
Muenchen. Simulations of laser-induced pion production
PSI. Consultancy on liquid mercury technology and metallurgical analysis.
RAL. Mechanical design and stress calculations in solid targets.

A group of CERN physicists with experience and knowledge in pion production solid and molten targets technology, beam dumps, safety, radioactivity inventory and shielding have been identified for part-time involvement. They will be constituted into a working group that would be the interface to the external laboratories.

Their first task would be to produce a conceptual design of the whole target area by addressing the need to combine operation of the target and collector with the disposal of the high-power, spent primary beam. In addition a detailed R&D programme can be started. It would tackle the following issues:

1. Identify the parameters of liquid metal targets that should be experimentally determined and the equipment needed for their measurement. Identify the theoretical base that the experimental results should benchmark.
2. Set up liquid jet equipment in the ISOLDE chemistry laboratory and demonstrate its use with mercury.
3. Organise a test in Europe of the injection of the mercury jet into a strong magnetic field.
4. Start planning the in-beam tests of the Hg-jet in the ISOLDE target area.
5. Calculations and irradiation tests for the toroid scheme proposed by RAL.

5.4 Horn

Several major questions are unanswered by the preliminary studies performed at the occasion of the NuFact99 in Lyon [11].

1. Can a horn be designed to provide focusing for particles emitted at large angle (approaching 90 degrees) from a long target?
2. What would be its performance compared with the 20 T solenoid option?
3. Can a horn be operated at a repetition rate of 75 Hz, with short pulses of typically 3 microseconds “flat” top?

4. At what peak current can such a horn be operated for a reasonable lifetime?
5. What design of power supply could be envisaged?

A small team is being set up to study these questions. Following this, a more formal proposal can be made for a systematic R&D on horns for a neutrino factory.

5.5 44/88 MHz scheme

Design of 44 MHz cavity and of 88 MHz cavity for 44/88 MHz scheme

The performance of the overall scheme, as well as the construction (physical length) and operating costs (electricity consumption) depend heavily upon the characteristics of the rf systems. Since these systems operate in unconventional conditions, R&D is especially important. Consequently, the following topics must be worked upon in the near future:

1. Design, construction and test of a high gradient 44 MHz cavity (including rf windows etc.)
2. Test of the maximum gradient capability in the presence of a solenoid field
3. Design, construction and test of the 1.8 Tesla superconducting solenoid
4. Study and test of different technological solutions for the beam windows
5. Study and development (with industry?) of high power – high efficiency rf amplifiers.

As an intermediate step in the investigations, interesting results can be achieved by transforming a PS 114 MHz cavity (after the end of LEP operation) into an 88 MHz resonator equipped with a solenoid.

5.6 Basic rf tests

1. Irradiation of 200 MHz cavity with (pulsed) magnetic field. A test of the breakdown properties of a high-field cavity under intense irradiation [24] has been performed in the AD target area. Its relevance is to the possible use of a rf system close to the target for capture and bunch rotation (not a part of the present reference scenario, but a necessary upgrade step to preserve muon polarisation).
2. Tests of a cavity with pressurised H_2 or He
3. Tests with a cavity closed by Li window (cooled)

5.7 Cavities for muon-linac (and RLA1)

Design of 200 MHz Nb sputtered Cu cavity (transforming existing 352 MHz LEP cavities). This is relates to the muon linear accelerator and, to beam loading problems in RLA1, since beam loading is reduced at lower rf frequencies due to the higher stored energy.

5.8 Recirculating linear accelerators

As is the case with the muon storage ring, the design of the recirculating linear accelerators is based on a series of assumptions concerning their engineering and the parameters of the muon beam. Once the feasibility of one or the other concept for muRLA1 and muRLA2 is established, all these assumptions ought to be questioned. If the assumed accelerating gradient was higher than 7 MV/m, the circumference of muRLA1 and muRLA2 would reduced almost in proportion, and so would be the decay losses. In the present design, about 77% of the muons survive through muRLA1 and muRLA2. Note that the reduction of the muRLA circumference may be undesirable for beam loading compensation considerations.

5.9 Muon storage ring

The design of the muon storage ring [18] is based on a number of assumptions concerning its engineering and the parameters of the injected muon beam. The next steps should put these issues on a firm ground. For the arcs, engineering concepts for all magnets should be developed.

1. Determine the inside dimensions of the vacuum chamber.
2. Determine the material (W?), temperature and shape of the shield that absorbs most of the power in the decay electrons and lets only a few W/m penetrate into the coils of the super-conducting magnets at liquid He temperature. This can be done using computer simulation with programs such as MARS.
3. Determine the number of layers and the dimensions of the coils, and propose better values for the magnetic field. In particular, answer the question up to what field the magnets can be built with a single coil layer.
4. Determine the shape of the coils at the ends of the magnets.
5. Determine the dimensions of the collars and steel yokes.
6. Study the installation of the magnets in cryostats, considering the pitch and roll angles, installation, alignment, and maintenance in the tunnel.

5.10 Muon test beams and front end instrumentation

It has become evident recently that beam tests of the most critical elements are needed for development of credible neutrino factory designs, in particular for the muon capture and cooling sections. An international working group is set-up to investigate the needs (energy, time structure, beam size, available testing area) and possibilities of muon test beams. From the CERN side, an evaluation of possible muon beams is undertaken, including reshuffling of a former neutrino beam line, from which a moderate intensity pulsed muon beam could be obtained. The international working group is expected to give a first report at the end of 2000. This is a place of choice for international collaboration, as muon beam lines are few and expensive, and it is not evident that appropriate ones exist now.

At the same time the instrumentation necessary to commission and run the aforementioned beam tests as well as the neutrino factory itself must be designed. Mini-workshops are taking place to define what parameters need to be measured, how and with which precision. The size and cost of the prototypes to be tested will depend on the outcome of these studies.

5.11 RAL Muon Scattering Experiment, MUSCAT, at Triumf

Ionisation cooling is now a feature of all current neutrino factory designs based on muon rings. The ionisation cooling process is a balance between the cooling effect of the energy loss and a heating effect due to multiple scattering. The studies performed so far on this balance and on the entire cooling procedure have relied on theory to determine the effect of multiple scattering, as there are no directly relevant measurements to use. The most applicable data comes from measurements of the scattering of 2.7 MeV/c electrons made over 55 years ago. This suggests that the scattering at high angle may be two times bigger than Moliere theory for light materials. Given the importance of ionisation cooling to the muon collider and neutrino factory projects, it is crucial that measurements are made with muons of approximately the correct momentum and compared directly with the theory being used in the simulations.

The purpose of the MUSCAT experiment [25] is to measure the angular distribution, in one dimension only, of muons scattered in various low Z target materials. For a detailed comparison with theory, this will be done at a number of different momenta for at least one of the materials. The targets to be used are liquid hydrogen, lithium hydride, lithium, beryllium, aluminium, and, if time allows, steel. These will be of a thickness to give a mean multiple scattering angle of about 10 mrad, i.e. about 10 cm of liquid hydrogen and a few mm or less of the other materials. The angular distribution will be measured up to about 3-4 times this value. The first experimental run took place during June/July 2000. A second run is being planned and mini-cooling extension to the experiment is under discussion. CERN is collaborating in this experiment.

CERN Reference Scenario parameter list

SPL Proton Driver	
Mean Beam Current during pulse, mA	11
Energy (kinetic), GeV	2.2
Invariant transverse rms emittance, µm	0.6
Beam energy spread (√5σ) MeV	±2
Bunch length (total: √5σ), ps	24
Linac length, m	800
rf frequency, MHz	352
Overall rf power, MW	31
Number of klystrons	46

Accumulator and Compressor rings		
	Accumulator	**Compressor**
Circumference, m	945	945
Beam kinetic energy, GeV	2.2	2.2
Revolution period (β=0.954), µs	3.3	3.3
rf harmonic number	146	146
Number of turns	660	~7
Repetition rate, Hz	75	75

44/88 MHz muon capture, phase rotation, cooling and acceleration system						
	Decay	**Rotation**	**Cooling I**	**Acceleration**	**Cooling II**	**Acceleration**
Length, m	30	30	46	32	112	≈450
Diameter, mm	600	600	600	600	300	200
Solenoid field, T	1.8	1.8	2.0	2.0	2.6	2.6
Frequency, MHz		44	44	44	88	88-200
Gradient, MV/m		2	2	2	4	4-10
Energy, MeV		200		280	300	2000

Recirculating Linacs	RLA1	RLA2
Injection energy, GeV	2	10
Extraction energy, GeV	10	50
Number of turns	4	4
Length of linacs (2), m	680	3813
Rf frequency, MHz	352	352
Bending radius in arc, m	5	25
Mean arc radius, m	20	100
Circumference, m	806	4442
Peak voltage gradient per linac,	7.4	7.4
Normalised admittance, mm rad	16.47	18.80
Normalised rms emittances, mm	1.83	2.09

Muon Decay Ring	
Design momentum, GeV	50
Muon fluence, s^{-1}	10^{14}
Configuration	Triangular
Normalised beam divergence in SS at σ_ε, mrad	0.1
Normalised beam emittance (σ_ε), mm rad	1.67
Aperture limit	3 σ_ε
Relative rms momentum spread	0.005
Bunch spacing, mm	851
Dipole field, T	6
Total length of straight sections, m	1500
Average radius in the arcs, m	46
Circumference, m	2075

Acknowledgments

The present work is the result of the effort of the Neutrino Factory Working Group. The Working Group comprises staff of CERN and other European laboratories and institutes. CERN is in contact with BNL, CEA, Cornell, FNAL, FZJ, GSI, INFN, IN2P3, KEK, LBL, PSI, RAL and TRIUMF for present and possible future collaborations. This external help has already been extremely valuable and will be essential in the future to succeed with the proposed R&D activities. The support of ECFA is gratefully acknowledged. The copy editor was CDJ.

References

1. C. Ankenbrandt et al Status of muon collider research and development and future plans. (Muon Collider Collaboration), Phys. Rev. ST Accel. Beams 2, 081001, (1999).
2. B. Autin, A, Blondel, J. Ellis, Eds. Perspective Study of Muon Storage Rings at CERN, CERN 99-02, ECFA 99-197, (1999).
3. S. Geer, C. Johnstone, D. Neuffer, Muon Storage Ring Neutrino Source: The Path to a Muon Collider? FERMILAB-TM-2073, (1999)
4. R. Palmer, C.D. Johnson, E. Keil, A Cost-Effective Design for a Neutrino Factory, CERN-SL-99-070, (1999).
5. N. Holtkamp, D. Finley, Eds. A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring, FERMILAB pub-00/08-E, (2000).
6. M. Vretenar, Ed. Report of the Study Group on a Superconducting Proton Linac as a PS Injector, CERN/PS 98-063 (RF-HP), (1998).
7. R Garoby, M. Vretenar, Status of the Proposal for a Superconducting Proton Linac at CERN, CERN/PS/ 99-064 (RF), (1999).
8. A. Lombardi, A 40-80 MHz system for phase rotation and cooling, CERN NUFACT-Note 20, (2000).
9. F. Dydak, Spokesperson, Proposal to study hadron production for the neutrino factory and for the atmospheric neutrino flux, HARP PS-214, CERN-SPSC/99-35, SPSC/P315, (1999)
10. C.D. Johnson, Study of the Behaviour of a Pulsed Liquid Jet Target, CERN NUFACT-Note 27, (2000).
11. The ICFA/ECFA Workshop "Neutrino Factories based on Muon Storage Rings", Lyon, Proceedings to be published in NIM-A (2000).
12. B. Autin, M. Chanel, M. Giovannozzi and M. Martini, Analysis of Different Options for a High Intensity Proton Driver for Neutrino Factory, CERN NUFACT-Note 16 (2000
13. K. Hanke, R. Scrivens, Simulation of an Induction Linac with Realistic Field Configuration CERN NUFACT-Note 17, (2000)
14. R. Garoby, D. Grier, E. Jensen, CERN. A. Mitra, R.L. Poirier, TRIUMF, The PS 40 MHz Bunching Cavity, 1997 Particle Accelerator Conference, 12-16.5.97, Vancouver, B.C., Canada (1997).
15. R. Garoby F. Gerig, Personal communication
16. E. Keil, http://wwwslap.cern.ch/~keil/MuMu/Doc/NFWG/19Apr00/19apr00.pdfSimulations of an
17. H. Burkhardt (ed.), ELFE at CERN: Conceptual Design Report, CERN 99-10 (1999).
18. E. Keil, A 50 GeV Muon Storage Ring Design, CERN Neutrino Factory Note 26, CERN SL/2000-013 AP (2000).
19. F. Zimmermann, Fringe Fields, Dynamic Aperture and Transverse Depolarisation in the CERN Muon Ring, CERN Neutrino Factory Note 22 (2000).

20. A. Verdier, Electron losses in the arcs of the muon storage ring, CERN Neutrino Factory Note 19 (2000)
21. E. Keil, http://nicewww.cern.ch/~nfwg/nufactwg/21/keil22mar00.pdf
22. E. Keil, http://nfwg.home.cern.ch/nfwg/nufactwg/26/EKeil.pdf
23. E. Keil, Permanent-Magnet Quadrupoles for Neutrino Factories, CERN Neutrino Factory Note 15 (2000).
24. W. Pirkl, Report in preparation, see also: http://cdj.home.cern.ch/cdj/public/rf/Proposal.htm
25. R. Edgecock, Spokesperson, http://hepunx.rl.ac.uk/neutrino-factory/muons/muscat.html
26. H. Haseroth (for the Neutrino Factory Working Group), Status of Studies for a Neutrino Factory at CERN, Proc. of the 7th European Particle Accelerator Conference, 26-30 June, Vienna, Austria
27. R. Cappi et al., Design of a 2 GeV Accumulator-Compressor for a Neutrino Factory, Proc. of the 7th European Particle Accelerator Conference, 26-30 June, Vienna, Austria
28. C.R. Prior et al, Synchrotron Based Proton Drivers for a Neutrino Factory, Proc. of the 7th European Particle Accelerator Conference, 26-30 June, Vienna, Austria
29. H. Schonauer et al, A Slow-Cycling Proton Driver for a Neutrino Factory, Proc. of the 7th European Particle Accelerator Conference, 26-30 June, Vienna, Austria
30. A. Lombardi et al., Phase Rotation, Cooling and Acceleration of Muon Beams: a Comparison of Different Approaches. To be published in the proceedings of LINAC2000.
31. The NuPECC Working Group on Radioactive Nuclear Beam Facilities, NuPECC April 2000.